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Bermudagrass Management in the Southern Piedmont USA: I. Soil and Surface Residue Carbon and Sulfur

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ABSTRACT

Improved forage management impacts on soil organic C and S depth distribution and surface residue accumulation could be large, but detailed temporal data are not available. We evaluated the factorial combination of three levels of N fertilization [inorganic, crimson clover (*Trifolium incarnatum* L.) cover crop plus inorganic, and broiler litter] and four levels of harvest strategy (unharvested, low grazing pressure, high grazing pressure, and hayed monthly) on soil bulk density, soil organic C, and total S, and surface residue C and S during the first 5 yr of 'Coastal' bermudagrass [*Cynodon dactylon* (L.) Pers.] management. Soil bulk density of the 0- to 6-cm depth responded very little to management, but across treatments it decreased 0.06 Mg m^{-3} yr^{-1} due to increasing soil organic matter with time. Soil organic C did not respond significantly to fertilization strategy during the 5 yr, but total S of the 0- to 6-cm depth was greater under broiler litter than under other fertilization strategies at the end of 3, 4, and 5 yr. Low and high grazing pressure were similar in their effect on soil organic C accumulation, averaging 140 g m^{-2} yr^{-1}. Most of the net change in soil organic C occurred in the 0- to 2-cm depth. Soil under unharvested and hayed management accumulated organic C at rates less than one-half of those observed under cattle grazing. Cattle grazing shunted C more directly from forage to the soil, which contributed to greater sequestration of soil organic C than with haying or unharvested management.

Soils in the humid southeastern USA have undergone severe erosion and degradation as a result of historically intensive conventional tillage for crop production (Trimble, 1974; Langdale et al., 1992). Soil organic C levels following long-term cultivation have been reported to be as low as 30% of precultivation levels (Giddens, 1957). Extreme losses of soil organic C have occurred in this region, because of accelerated decomposition with cultivation and erosive forces, which preferentially remove the lower density components of soil (i.e., organic matter) concentrated near the surface (Lowrance and Williams, 1988). Sequestration of organic C in previously degraded soils is necessary to not only improve the physical, chemical, and biological properties of soils (Follett et al., 1987), but also to help mitigate potential greenhouse effects from rising atmospheric CO_2 levels (Lal et al., 1998).

Restoration of eroded cropland in the southeastern USA is possible with conservation tillage systems, which minimize soil disturbance and maximize surface residue accumulation (Langdale et al., 1992). In the Southern Piedmont region, however, an increasing portion of land supports small-farm, cattle-grazing production systems (Census of Agriculture, 1992). Despite the abundance and importance of managed pastures in the southeastern USA, relatively little information is available to describe rates of soil organic C and N accumulation under pasture management systems (Schnabel et al., 2001).

Grazing of a forage crop compared with haying returns much of the manure directly to the land with a positive impact on soil organic C and N accumulation (Franzluebbers et al., 2000), but the impact of stocking density on plant productivity, soil compaction, and soil organic C and S cycling is not well understood. Further, the impact of not harvesting forage on soil organic C and S deserves attention, based on the extent of land currently managed under the Conservation Reserve Program (CRP). Harvest management would be expected to alter the distribution of C and S among surface residue and the soil profile because of the effects of animal traffic, ruminant processing of forage, and forage removal.

The effect of fertilization strategy on soil organic C dynamics in managed pastures is variable (Schnabel et al., 2001). In some cases, increased fertilization may improve forage yield but have little effect on soil organic C (Owensby et al., 1969; Jenkinson, 1988; Ross et al., 1995). In other cases, increased fertilization improves both forage yield and soil organic C in the long term (Schwab et al., 1990; Haynes and Williams, 1992; Malhi et al., 1997). The impact on soil organic C and S dynamics of whether fertilization comes from an organic or an inorganic source has received limited attention, but is a very important issue in the southeastern USA, where poultry production and associated availability of manure are abundant. Soil organic C was little affected whether grass received manure or inorganic fertilizer in a long-term experiment at Rothamsted (Jenkinson, 1988). However, greater accumulation of soil organic C was observed under fertilized ryegrass (*Lolium perenne* L.) than under ryegrass–white clover (*Trifolium repens* L.) (Hatch et al., 1991). Much more work is needed to understand the sequestration of soil organic C and S in response

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Abbreviations: CRP, Conservation Reserve Program.

to organic and inorganic amendments to grazed and ungrazed pastures.

We hypothesized that with equivalent amounts of total N applied, fertilization strategy (i.e., inorganic and organic) could affect the availability of N to forage and could therefore affect the quality and quantity of forage, leading to differences in soil organic C and S sequestration rates. In addition, we wanted to ascertain the impact of forage harvest strategy (i.e., grazed and ungrazed) on soil compaction and cycling of C and S during the first 5 yr of grass management following conversion from long-term cultivated cropland.

Table 1. Characteristics and rates of fertilizer sources applied.

Variable	1994	1995	1996	1997	1998	5-yr mean
			Inorganic			
N, g m^{-2}	21.1	20.2	25.0	23.8	22.4	22.5
			Cover + inorganic			
N, g m^{-2}	21.1	10.1	13.2	12.0	11.1	13.5
			Broiler litter			
Dry mass, g m^{-2}	522	650	519	502	504	539
C, g m^{-2}	183	205	169	193	166	183
S, g m^{-2}	2.0	2.6	2.6	2.3	1.7	2.2
N, g m^{-2}	19.5	21.6	16.4	22.3	17.2	19.4

Broiler litter contained 26 ± 4% moisture on a gravimetric basis.

MATERIALS AND METHODS

Site Characteristics

A 15-ha upland field (33° 22′N, 83° 24′W) in the Greenbrier Creek subwatershed of the Oconee River watershed near Farmington, GA had previously been conventionally cultivated with wheat (*Triticum aestivum* L.), soybean [*Glycine max* (L.) Merr.], sorghum [*Sorghum bicolor* (L.) Moench], and cotton (*Gossypium hirsutum* L.) for several decades prior to grassland establishment by sprigging of Coastal bermudagrass in 1991. Mean annual temperature is 16.5°C, rainfall is 1250 mm, and potential evaporation is 1560 mm. Sampled on a 30-m grid, the frequency of soil series was 46% Madison, 22% Cecil, 13% Pacolet, 5% Appling, 2% Wedowee (fine, kaolinitic, thermic Typic Kanhapludults), 11% Grover (fine-loamy, micaceous, thermic Typic Hapludults), and 1% Louisa (loamy, micaceous, thermic, shallow Ruptic-Ultic Dystrudepts). Soil textural frequency of the Ap horizon was 75% sandy loam, 12% sandy clay loam, 8% loamy sand, and 4% loam. Depth of the Ap horizon was 21 ± 12 cm.

Experimental Design

The experimental design was a randomized complete block with treatments in a split-plot arrangement in each of three blocks, which were delineated by landscape features (i.e., slight, moderate, and severe erosion classes). Main plots were fertilization strategy ($n = 3$) and split-plots were harvest strategy ($n = 4$), for a total of 36 experimental units. Individual paddocks were 0.69 ± 0.03 ha. Spatial design of paddocks minimized runoff contamination and handling of animals through a central roadway. Each paddock contained a 3 by 4 m shade, mineral feeder, and water trough placed in a line 15 m long near the top of the landscape. Unharvested and hayed exclosures within each paddock were 100 m^2.

Fertilization strategy consisted of (i) inorganic only (~20 g N m^{-2} yr^{-1} as NH_4NO_3 broadcast in split applications in May and July), (ii) crimson clover cover crop plus supplemental inorganic fertilizer (~20 g N m^{-2} yr^{-1} with one-half of the N assumed fixed by clover biomass and the other half as NH_4NO_3 broadcast in July), and (iii) broiler litter (~20 g N m^{-2} yr^{-1} broadcast in split applications in May and July). Details of fertilizer applications each year are reported in Table 1. Phosphorus and K applications varied among treatments because excess P and K were applied with broiler litter (12.4 ± 4.0 g P m^{-2} yr^{-1} and 16.7 ± 4.8 g K m^{-2} yr^{-1}) to meet N requirements, while diammonium phosphate and potash were applied based on soil testing recommendations (1.6 ± 1.1 g P m^{-2} yr^{-1} and 5.2 ± 4.1 g K m^{-2} yr^{-1} for inorganic fertilizer and 2.3 ± 2.0 g P m^{-2} yr^{-1} and 5.5 ± 4.1 g K m^{-2} yr^{-1} for crimson clover cover crop plus supplemental inorganic fertilizer). Crimson clover was direct drilled in clover treatments at ~1 g m^{-2} in October each year. All paddocks were mowed in late April following soil sampling and residue allowed to decompose [i.e., clover biomass in clover plus inorganic treatment and winter annual weeds (primarily *Lolium annuum* L. and *Bromus catharticus* Vahl.) in other treatments].

Harvest strategy mimicked a gradient in forage utilization consisting of (i) unharvested (biomass cut and left in place at the end of growing season), (ii) low grazing pressure (put-and-take system to maintain a target of ~300 g m^{-2} of available forage), (iii) high grazing pressure (put-and-take system to maintain a target of ~150 g m^{-2} of available forage), and (iv) hayed monthly to remove aboveground biomass at 4-cm height. Yearling Angus steers (*Bos taurus*) grazed paddocks during a 140-d period from mid May until early October each year, except during the first year of treatment implementation (1994) when grazing began in July due to repairs to infrastructure following a tornado. No grazing occurred in the winter. Animals were weighed, available forage determined, and paddocks restocked on a monthly basis.

Sampling and Analyses

Soil and surface residue were sampled in April prior to grazing and in October following grazing during most years. Hayed and unharvested exclosures were sampled in July, rather than May during 1994. Sampling locations within grazed paddocks were within a 3-m radius of points on a 30-m grid. Due to the nonuniform dimensions of paddocks, sampling sites within a paddock varied from as few as four to as many as nine, averaging seven ± one. Two sampling locations were fixed within each hayed and unharvested exclosure. Surface residue was collected from a 0.25-m^2 area at each sampling point following removal of vegetation at a height of ≈4 cm. Surface residue, including plant stubble, was cut to the mineral surface with battery-powered hand shears, bagged, and dried at 70°C for several days. During 1994 and 1995, soil was sampled at depths of 0 to 2, 2 to 4, and 4 to 6 cm from the composite of two 8.5-cm-diam. cores within each sampling location. From spring 1996 until the spring of 1998, soil was sampled to the same depths from the composite of nine 4.1-cm-diam. cores within each sampling location. Soil was air dried and ground to <2 mm in a mechanical grinder in 1994 and 1995. Soil was oven dried (55°C, 72 h) and gently crushed to pass a 4.75-mm screen in all other years.

Beginning in February 1999, sampling strategy was changed (i) to collect surface residue and soil only once per year, (ii) to more directly address the zonal changes in pastures in response to animal behavior near shade and water sources, and (iii) to collect soil to deeper depths. Surface residue was collected from a composite of eight 0.04-m^2 areas randomly selected within each of three zones within paddocks (i.e., 0–30, 30–70, and 70–120 m distances from livestock shades) and within each exclosure. Surface residue was processed as de-

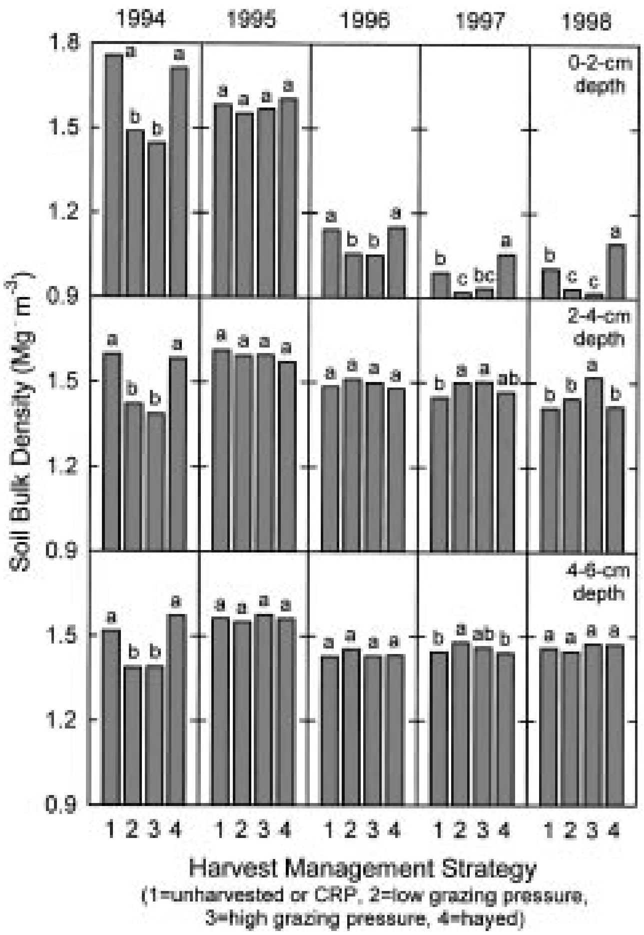

Fig. 1. Soil bulk density at depths of 0 to 2, 2 to 4, and 4 to 6 cm as affected by harvest strategy (averaged across fertilization strategies) during spring sampling events of the first 4.5 yr of management. Bars with a different letter within a sampling event and within a soil depth indicate significance at $P \leq 0.1$.

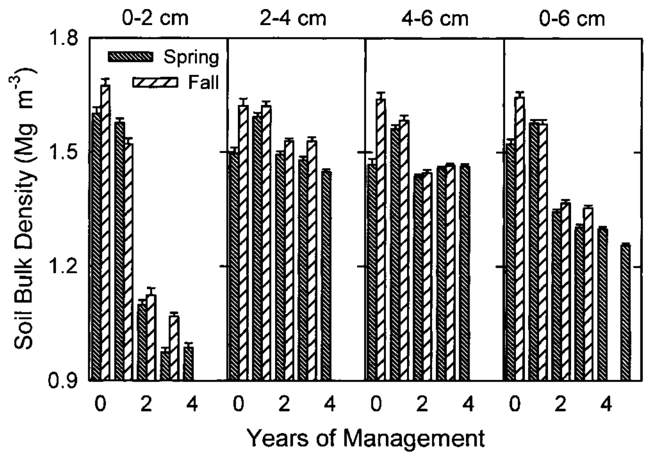

Fig. 2. Soil bulk density at depths of 0 to 2, 2 to 4, 4 to 6, and 0 to 6 cm as affected by spring and fall sampling (averaged across fertilization and harvest strategies) during the first 5 yr of management. Error bars are standard errors of means (n = 36).

scribed previously. A single 4.1-cm-diam. soil core was collected from each of the eight residue sampling sites and composited. Soil was collected at depths of 0 to 3, 3 to 6, 6 to 12, and 12 to 20 cm, oven dried (55°C, 72 h), and gently crushed to pass a 4.75-mm screen.

Soil bulk density was calculated from the oven-dried soil weight (55°C) and pooled-core volume ($2.26–8.45 \times 10^{-4}$ m^3, depending on depth of sampling). During 1994 and 1995, soil was collected by scooping to a particular depth by a highly experienced technician. To mechanize the process independent of experience, a tray with slots at 2, 4, and 6 cm for cutting soil sections with precision was used in 1996, 1997, and 1998. In 1999, soil was cut to depth inside the sampling tube. Surface residue was ground to <1 mm and a 20- to 30-g soil subsample from each composite sample was ground to a fine powder in a ball mill for 3 min prior to analysis of total C and S with dry combustion at 1350°C (Leco CNS-2000, St. Joseph, MI).[1] It was assumed that total C was equivalent to organic C because soil pH was near 6.

Data from multiple samples within an experimental unit were averaged and not considered as a source of variation in the analysis of variance (SAS Institute, 1990). Within-depth, across-depth, within-year, and across-year analyses were conducted according to the split-plot design with three blocks. Across-depth analyses considered the bulk density of soil in calculating standing stock values of soil organic C and total S. Across-year analyses considered years as repeated measures. Effects were considered significant at $P \leq 0.1$.

RESULTS AND DISCUSSION

Soil Bulk Density

Within a sampling event, soil bulk density varied mostly due to depth and harvest strategy (Fig. 1). Averaged across sampling events, soil bulk density was 1.29 Mg m^{-3} at a depth of 0 to 2 cm, 1.54 Mg m^{-3} at a depth of 2 to 4 cm, and 1.50 Mg m^{-3} at a depth of 4 to 6 cm. At a depth of 0 to 2 cm, soil bulk density in spring was often greater when forage was unharvested or hayed compared with grazing, especially later in the 5-yr evaluation period (Fig. 1). In contrast, soil bulk density at a depth of 2 to 4 cm was often lower when forage was unharvested or hayed compared with grazing, especially later in the 5-yr evaluation period. Small and inconsistent changes in soil bulk density occurred at a depth of 4 to 6 cm throughout the 5 yr.

Soil bulk density at a depth of 0 to 6 cm was often higher when sampled in fall than when sampled in spring (Fig. 2). Contributions to this effect occurred at all sampling depths, but were most consistent at a depth of 2 to 4 cm. Part of this difference was probably due to cattle traffic during the summer, which would have increased bulk density (Lull, 1959). On a western rangeland in Wyoming, soil bulk density of the 0- to 5-cm depth increased by 0.09 Mg m^{-3} in the fall compared with the spring due to cattle grazing in 1 yr, but was unaffected by sampling time in another year (Abdel-Magid et al., 1987). Soil moisture was often lower in fall than in spring in our study, and this may have also partly contributed to higher estimates in fall compared with spring.

Soil bulk density also tended to decrease with increasing number of years under forage management (Fig. 2).

[1] Trade and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the U.S. Department of Agriculture.

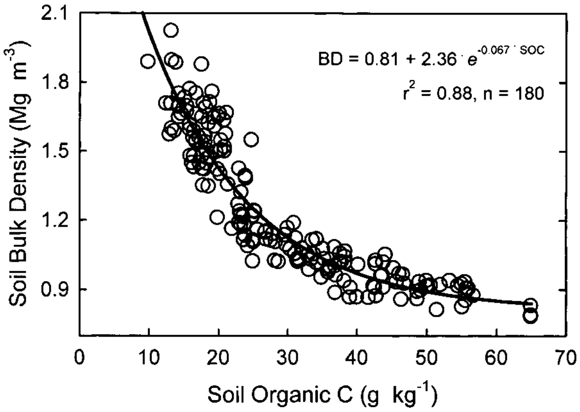

Fig. 3. Relationship between soil bulk density and soil organic C concentration. Data are from 0- to 2-cm depth from each of the fertilization and harvest strategies during 1994 to 1998.

At a depth of 0 to 6 cm when sampled in spring, soil bulk density decreased an average of 0.06 Mg m^{-3} yr^{-1}, based on the slope of a linear regression. Part of this effect might have been due to the change in sampling protocol between 1995 and 1996, but further decreases were also observed after the change in protocol. Soil bulk density decreased with time, most likely because of the increase in soil organic matter near the soil surface, as well as greater volume of roots with time. A strong inverse relationship occurred between soil organic C and bulk density (Fig. 3). Soil organic matter is lighter than mineral soil and is also a food source for soil organisms, which then contribute to increasing porosity and water-stable aggregation (Oades, 1993). A similar inverse relationship between soil organic C and bulk density was observed under various long-term management systems in Georgia (Franzluebbers et al., 2000).

Soil Organic Carbon and Total Sulfur

Soil organic C concentration was relatively uniform with soil depth beginning in 1994 and progressively became more stratified with depth (Fig. 4). In April 1996 at the end of 2 yr of management, soil organic C concentration under grazed systems was greater at a depth of 0 to 2 cm compared with unharvested and hayed management. In April 1996, soil organic C concentration under high grazing pressure was also higher than under low grazing pressure. Interactions occurred between fertilization and harvest strategies at other depths, but were minor in magnitude and not consistent across years.

In April 1998 at the end of 4 yr of management, soil organic C concentration at a depth of 0 to 2 cm remained greater when grazed than when ungrazed under all three fertilization strategies (Fig. 4). At this sampling, soil organic C concentration at a depth of 0 to 2 cm under unharvested management was greater than under hayed management when fertilized inorganically and with broiler litter, but not significantly different with clover. With broiler litter fertilization, soil organic C concentration was also greater when unharvested than when hayed at a depth of 2 to 4 cm. Soil organic C concentration at a depth of 2 to 4 cm was greater when grazed than

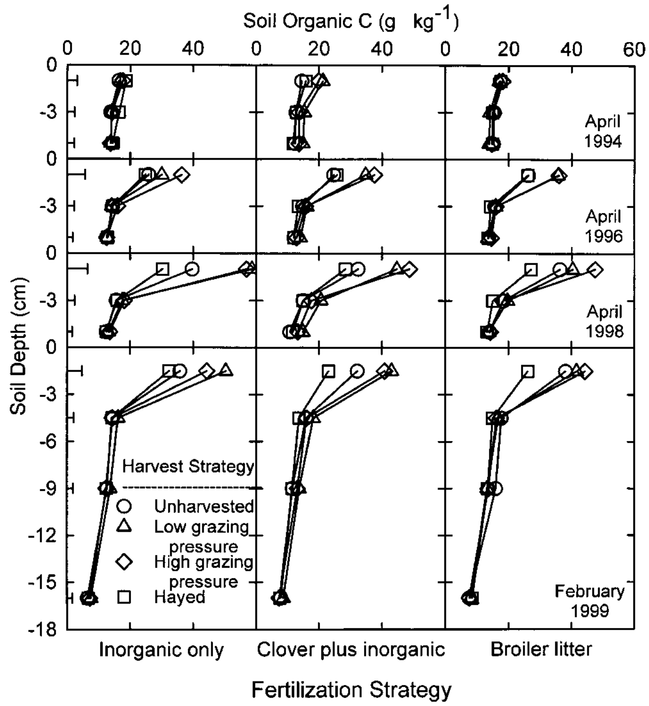

Fig. 4. Soil organic C depth distribution as affected by fertilization and harvest strategies during the first 5 yr of management. Horizontal bars originating at the left vertical axis indicate LSD at *P* = 0.1 to separate all combinations of fertilization and harvest strategies within a soil depth.

when ungrazed under all three fertilization strategies. Across harvest management, fertilization strategy had no effect on soil organic C concentration at any depth in April 1998.

In February 1999 at the end of 5 yr of management, soil organic C concentration continued to be greater under grazed than under ungrazed management in all three fertilization strategies at a depth of 0 to 3 cm (Fig. 4). At this depth, soil organic C concentration under low grazing pressure was greater than under high grazing pressure with inorganic fertilization. Also, soil organic C concentration under unharvested management was greater than under hayed management with clover and broiler litter fertilization, but not with inorganic fertilization. Below 3 cm, soil organic C concentration was unaffected by harvest and fertilization strategies.

The standing stock of soil organic C averaged across fertilization strategies increased with time under forage management the most at a depth of 0 to 2 cm, intermediately at a depth of 2 to 4 cm, and not at all at a depth of 4 to 6 cm (Fig. 5). Both low and high grazing pressures sequestered three to six times more soil organic C than unharvested and hayed management at depths of 0 to 2 and 2 to 4 cm. Unharvested management sequestered approximately twice the soil organic C as hayed management, in which aboveground biomass was removed. Fertilization strategy had significant, but inconsistent effects on the standing stock of soil organic C at a depth of 0 to 6 cm, depending on harvest strategy and time of sampling (Table 2).

Broiler litter fertilization added an average of 183 g m^{-2} yr^{-1} of C (Table 1). To assess the contribution of

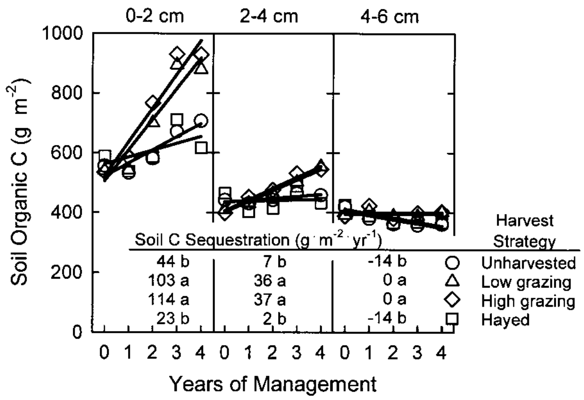

Fig. 5. Soil organic C content at depths of 0 to 2, 2 to 4, and 4 to 6 cm as affected by harvest strategy (averaged across fertilization strategies) during the first 4 yr of management. Soil organic C sequestration values are for each of the soil depths and different letters within a soil depth indicate significance at $P \leq 0.1$.

C from broiler litter to the overall rate of soil organic C sequestration, we took the difference in standing stock of C at a depth of 0 to 6 cm between broiler litter and inorganic fertilization strategies and regressed this difference on time. Only with unharvested management was there an increase in soil organic C with broiler litter compared with inorganic fertilization. The increase (37 g m^{-2} yr^{-1}) was equivalent to 20% of the total C added. In grazed treatments and hayed management, soil organic C sequestration due to broiler litter fertilization was lower than under inorganic fertilization (-3 to -44 g m^{-2} yr^{-1}). These calculations suggest that decomposition of broiler litter is rapid in this environment. However, it is also possible that inorganic fertilization stimulated plant production more than broiler litter fertilization, resulting in greater plant C fixation and deposition of associated residue and manure to soil. This effect would have masked our ability to detect soil organic C sequestration due to broiler litter application using a difference technique. In addition, the quantity of C added in broiler litter was relatively small compared with the much larger standing stock of C in surface soil. The quantity of C applied in broiler litter each year was similar to the LSD among treatments within a sampling event (0.15 ± 0.02 kg m^{-2}, mean $\pm$ standard deviation among six sampling events).

The standing stock of total soil S at a depth of 0 to 6 cm was greater under broiler litter than under inorganic and clover fertilization strategies beginning in April 1996 and continuing each sampling event thereafter (Table 3). Broiler litter fertilization added an average of 2.2 g m^{-2} yr^{-1} of S (Table 1), of which 76% was retained in the standing stock of total S in soil (0–6 cm) and residue when averaged across harvest management strategies (calculating the difference between broiler litter and inorganic fertilization with time). Soil organic matter formations would have sequestered a part of this added S, but unlike soil organic C dynamics with a dominant atmospheric flux, the mineralization of organic S leads to sulfate accumulation in soil solution, which can be either leached or retained in soil (Stevenson and Cole, 1999). It appears that only a small fraction of the S added in broiler litter was leached beyond the upper 6 cm of soil.

The stock of total soil S was greater under grazed

Table 2. Carbon stock in soil and residue (kg m^{-2}) as affected by fertilization strategy (inorganic, clover, and broiler litter) and harvest strategy [unharvested (UH), low grazing pressure (LG), high grazing pressure (HG), and hayed (H)] during the first 5 yr of forage management.

	Inorganic					Clover + inorganic					Broiler litter					$LSD_{(P=0.1)}$	
Property	UH	LG	HG	H	Mean	UH	LG	HG	H	Mean	UH	LG	HG	H	Mean	All	Means
								April 1994									
Soil (0–6 cm)	1.44	1.30	1.31	1.62	1.42	1.33	1.43	1.31	1.36	1.35	1.48	1.30	1.35	1.46	1.40	0.18	0.09
Residue	0.17	0.12	0.12	0.14	0.14	0.24	0.13	0.19	0.25	0.20	0.15	0.09	0.12	0.16	0.13	0.05	0.03
Soil + residue	1.62	1.42	1.42	1.76	1.56	1.57	1.56	1.50	1.61	1.56	1.64	1.40	1.47	1.62	1.53	0.17	0.09
								April 1995									
Soil (0–6 cm)	1.36	1.33	1.47	1.37	1.38	1.24	1.40	1.42	1.17	1.31	1.43	1.41	1.48	1.46	1.45	1.14	0.07
Residue	0.76	0.63	0.24	0.09	0.43	0.77	0.78	0.33	0.14	0.51	0.50	0.61	0.23	0.09	0.36	0.22	0.11
Soil + residue	2.12	1.96	1.72	1.46	1.81	2.01	2.17	1.76	1.31	1.81	1.93	2.02	1.72	1.55	1.81	0.20	0.10
								April 1996									
Soil (0–6 cm)	1.40	1.48	1.62	1.38	1.47	1.34	1.61	1.60	1.33	1.47	1.41	1.58	1.65	1.38	1.50	0.15	0.07
Residue	0.89	0.45	0.17	0.11	0.40	0.76	0.37	0.19	0.10	0.35	0.51	0.30	0.11	0.07	0.25	0.17	0.08
Soil + residue	2.30	1.93	1.79	1.49	1.88	2.10	1.97	1.79	1.43	1.83	1.92	1.88	1.75	1.45	1.75	0.22	0.11
								April 1997									
Soil (0–6 cm)	1.47	1.85	1.85	1.51	1.67	1.42	1.76	1.85	1.60	1.66	1.59	1.74	1.89	1.60	1.71	0.14	0.07
Residue	0.81	0.20	0.06	0.10	0.29	0.54	0.21	0.08	0.08	0.23	0.66	0.14	0.04	0.06	0.23	0.18	0.09
Soil + residue	2.27	2.05	1.91	1.60	1.96	1.96	1.97	1.93	1.68	1.89	2.25	1.88	1.93	1.66	1.93	0.19	0.10
								April 1998									
Soil (0–6 cm)	1.59	1.91	1.95	1.44	1.72	1.37	1.84	1.84	1.40	1.61	1.62	1.76	1.85	1.41	1.66	0.11	0.05
Residue	0.29	0.14	0.06	0.07	0.14	0.15	0.12	0.05	0.08	0.10	0.26	0.09	0.06	0.04	0.11	0.07	0.03
Soil + residue	1.89	2.05	2.02	1.50	1.86	1.52	1.95	1.89	1.48	1.71	1.88	1.85	1.90	1.45	1.77	0.12	0.06
								February 1999									
Soil (0–6 cm)	1.70	2.05	1.95	1.72	1.86	1.66	2.07	2.03	1.47	1.81	1.86	1.92	2.03	1.58	1.85	0.16	0.08
Residue	0.33	0.27	0.18	0.10	0.22	0.23	0.20	0.13	0.08	0.16	0.18	0.16	0.14	0.08	0.14	0.05	0.03
Soil + residue	2.03	2.32	2.13	1.82	2.08	1.90	2.26	2.17	1.55	1.97	2.04	2.08	2.17	1.66	1.99	0.17	0.09
Soil 2 (0–20 cm)	3.69	4.28	3.99	3.76	3.93	3.75	4.42	4.18	3.51	3.97	4.26	4.15	4.25	3.91	4.14	0.41	0.20
Soil 2 + residue	4.02	4.55	4.17	3.86	4.15	3.98	4.61	4.32	3.59	4.13	4.43	4.31	4.39	3.99	4.28	0.43	0.21

than under ungrazed management beginning in April 1996 with an increasing effect thereafter (Table 3). Beginning in April 1998, the standing stock of total soil S was also greater under unharvested compared with hayed management. In general, these effects were similar to those observed for the standing stock of soil organic C. However, unlike soil organic C, the standing stock of total soil S did not increase significantly with time under forage management.

Surface Residue Carbon and Sulfur

Surface residue C and S contents were relatively small, but significant components of the total standing stock of C and S (Tables 2 and 3). Surface residue C content averaged 10, 31, 19, 13, 7, and 9% of total standing stock of C in 1994, 1995, 1996, 1997, 1998, and 1999, respectively. Surface residue S content averaged 7, 13, 15, 10, 7, and 5% of total standing stock of S in those same years, respectively.

At the beginning of forage management in April 1994, surface residue C and S contents were little affected by fertilization and harvest management strategies (Tables 2 and 3). Beginning in April 1995, surface residue C and S contents were inversely proportional to the level of forage utilization; that is, surface residue C and S (i) were highest with unharvested management in which forage was cut and left on the soil surface to decompose, (ii) decreased with increasing level of grazing pressure, and (iii) were lowest with hay removal (Tables 2 and 3; Fig. 6). The lower surface residue C and S contents under grazing compared with unharvested management and under high grazing pressure compared with low grazing pressure implies that cattle processed a large amount of forage and reduced the residence time of C and S flowing from forage to residue to soil. Combined

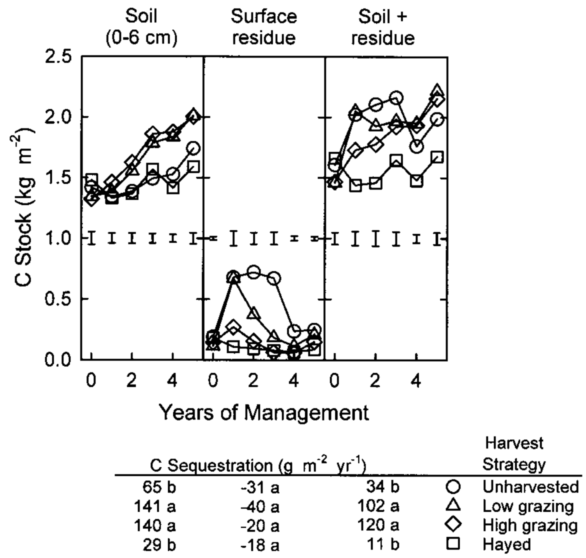

Fig. 6. Carbon stock in soil at a depth of 0 to 6 cm, in surface residue, and in soil plus residue as affected by harvest strategy (averaged across fertilization strategies) during the first 5 yr of management. Vertical bars are LSD at $P = 0.1$ to separate means among harvest strategies within a year. Carbon sequestration values are based on linear regression for each of the system components (i.e., soil, residue, and soil + residue). Different letters following C sequestration rates within a soil–residue component indicate significance at $P \leq 0.1$.

Table 3. Sulfur stock in soil and residue (g m^{-2}) as affected by fertilization strategy (inorganic, clover, and broiler litter) and harvest strategy [unharvested (UH), low grazing pressure (LG), high grazing pressure (HG), and hayed (H)] during the first 5 yr of forage management.

	Inorganic					Clover + inorganic					Broiler litter					LSD$_{(P=0.1)}$	
Property	UH	LG	HG	H	Mean	UH	LG	HG	H	Mean	UH	LG	HG	H	Mean	All	Means
								April 1994									
Soil (0–6 cm)	17.5	14.8	16.2	18.5	16.7	11.4	12.1	11.1	12.4	11.8	12.4	11.7	13.1	13.5	12.7	3.8	1.9
Residue	1.1	0.7	0.7	0.9	0.9	1.4	0.8	1.1	1.5	1.2	1.1	0.7	0.8	1.1	0.9	0.3	0.2
Soil + residue	18.6	15.5	16.9	19.3	17.6	12.8	12.9	12.2	13.9	12.9	13.5	12.3	13.9	14.5	13.6	3.7	1.8
								April 1995									
Soil (0–6 cm)	13.7	10.5	15.8	12.4	13.1	9.4	9.9	10.1	9.3	9.7	11.7	13.0	14.0	13.0	12.9	3.5	1.8
Residue	2.4	2.7	1.5	0.4	1.7	2.8	3.2	1.7	0.6	2.1	1.9	2.9	1.5	0.4	1.7	0.7	0.3
Soil + residue	16.1	13.2	17.3	12.8	14.9	12.2	13.1	11.8	10.0	11.8	13.6	15.9	15.4	13.4	14.6	3.4	1.7
								April 1996									
Soil (0–6 cm)	10.0	10.6	10.9	11.7	10.8	8.1	10.0	10.6	8.2	9.2	10.0	11.9	14.8	10.2	11.7	2.7	1.4
Residue	4.1	2.9	1.2	0.6	2.2	3.5	1.9	1.3	0.6	1.8	2.4	1.8	0.8	0.4	1.4	0.7	0.4
Soil + residue	14.1	13.5	12.0	12.3	13.0	11.6	11.9	11.9	8.8	11.1	12.4	13.7	15.5	10.7	13.1	2.8	1.4
								April 1997									
Soil (0–6 cm)	11.3	12.3	12.2	9.5	11.3	8.8	11.5	12.7	9.1	10.5	12.2	15.1	17.4	11.1	14.0	2.0	1.0
Residue	3.8	1.3	0.4	0.5	1.5	2.3	1.2	0.5	0.4	1.1	3.3	1.0	0.3	0.3	1.2	0.8	0.4
Soil + residue	15.1	13.6	12.6	10.1	12.9	11.1	12.8	13.2	9.5	11.6	15.5	16.1	17.7	11.5	15.2	1.9	1.0
								April 1998									
Soil (0–6 cm)	11.2	13.4	15.2	8.5	12.1	9.8	11.9	13.4	7.8	10.7	13.0	17.2	18.2	9.4	14.4	1.8	0.9
Residue	2.8	0.8	0.4	0.5	1.1	1.5	0.7	0.3	0.8	0.8	1.5	0.5	0.4	0.2	0.7	0.5	0.3
Soil + residue	14.0	14.2	15.6	9.0	13.2	11.3	12.6	13.8	8.5	11.6	14.5	17.7	18.6	9.6	15.1	1.9	0.9
								February 1999									
Soil (0–6 cm)	21.8	25.3	22.0	14.4	20.9	17.7	24.5	28.1	7.9	19.6	23.9	35.3	37.7	12.8	27.4	5.7	2.8
Residue	2.1	1.7	1.3	0.6	1.4	1.4	1.2	1.0	0.4	1.0	1.1	1.0	1.0	0.4	0.9	0.4	0.2
Soil + residue	23.9	27.0	23.3	15.0	22.3	19.2	25.7	29.0	8.3	20.5	25.1	36.3	38.7	13.2	28.3	5.7	2.9
Soil 2 (0–20 cm)	39.0	38.5	29.3	23.8	32.6	24.1	33.6	36.5	12.7	26.7	31.3	45.8	47.4	19.2	35.9	9.5	4.8
Soil 2 + residue	41.1	40.2	30.6	24.4	34.1	25.4	34.8	37.5	13.1	27.7	32.4	46.8	48.4	19.6	36.8	9.6	4.8

with the observation of greater soil organic C and total S accumulation under grazing than under unharvested management, it can be concluded that cattle grazing shunted C more directly from forage to the soil organic C pool compared with nonutilization of forage (Fig. 6). Grazing animals consume and utilize digestible components of forage and excrete more resistant fractions of forage (Fisher et al., 1995). Cattle grazing appears to have benefitted the storage of C in soil, at least in the first 5 yr of forage management. The positive effect of cattle grazing compared with unharvested management on soil organic C storage was also observed on a mixed-grass prairie at the end of 11 yr in Wyoming (Manley et al., 1995). At the end of 15 to 19 yr of bermudagrass management in Georgia, grazed pastures had 0.18 kg surface residue C m^{-2} and hayed fields had 0.12 kg surface residue C m^{-2} (Franzluebbers et al., 2000), similar in magnitude and effect to our observations at the end of 5 yr of bermudagrass management (Table 2).

Total standing stock of C (soil + residue) to a depth of 20 cm in February 1999 at the end of 5 yr of management was 4.19 $\pm$ 0.30 kg m^{-2} (mean $\pm$ standard deviation among 12 treatments) (Table 2). Averaged across harvest strategies, total standing stock of C was unaffected by fertilization strategy. With inorganic and with clover plus inorganic fertilization, grazing increased the stock of C compared with ungrazed treatments. With broiler litter fertilization, total standing stock of C under unharvested management was equivalent to that under grazed treatments, but greater than that under hayed management. As a fraction of the total standing stock of C, soil organic C at a depth of 0 to 6 cm was consistent at 0.44 $\pm$ 0.02. Measurement of only the 0- to 6-cm soil depth during the first 4 yr appears to have been adequate to detect most of the changes in soil organic C concentration due to management variables in this environment.

Soil Organic Carbon Sequestration

The rate of accumulation in soil organic C during the first 5 yr under hayed management (29 g m^{-2} yr^{-1}; Fig. 6) was very similar to the estimated rate under hayed bermudagrass in a chronosequence study at a nearby location (35 g m^{-2} yr^{-1} interpolated from the first 5 yr; Franzluebbers et al., 2000). In addition, our results of greater soil C sequestration under grazing compared with haying (a difference of 111 g m^{-2} yr^{-1}; Fig. 6) are somewhat higher than from observations between grazed and hayed bermudagrass at a nearby location (42 g m^{-2} yr^{-1} during a 15–19 yr comparison; Franzluebbers et al., 2000). It could be expected that C sequestration rates in this previous study were higher during the initial 5 yr than those 5 to 10 yr later.

Soil organic C sequestration under unharvested management (65 g m^{-2} yr^{-1}; Fig. 6) was similar to the estimated rate of soil organic C sequestration during 5 yr of unharvested grass management under CRP at six locations in Kansas, Nebraska, and Texas (58 $\pm$ 66 g m^{-2} yr^{-1} at a depth of 0 to 20 cm, 39 $\pm$ 47 g m^{-2} yr^{-1} at a depth of 0 to 10 cm, and 25 $\pm$ 30 g m^{-2} yr^{-1} at a depth of 0 to 5 cm; Gebhart et al., 1994). We fertilized the unharvested management system to obtain a more direct comparison with other harvest management strategies, but most landowners are unlikely to fertilize unharvested grass in CRP on a yearly basis. Fertilization may have increased the rate of soil organic C sequestration by allowing more plant biomass to accumulate. However, our observation of greater soil organic C sequestration under grazing compared with unharvested management is consistent with observations in a semi-arid mixed grass prairie in Wyoming (Manley et al., 1995).

For the most part, broiler litter application did not affect soil organic C accumulation compared with inorganic and clover plus inorganic fertilization strategies. This was probably due to the relatively low rate of application (i.e., 0.54 $\pm$ 0.06 kg dry mass m^{-2} yr^{-1}; Table 1). However, no change in soil organic matter was observed at the end of 2 yr following a single application of either 2.2 or 13.4 kg m^{-2} of broiler litter on a similar Cecil sandy loam (Jackson et al., 1977). In contrast, broiler litter application (1.09 $\pm$ 0.54 kg dry mass m^{-2} yr^{-1}) resulted in greater soil organic C concentration at a depth of 0 to 15 cm than without broiler litter in a survey of 12 paired pastures in northern Alabama at the end of 21 $\pm$ 4 yr (Kingery et al., 1994). The estimated mean rate of soil organic C accumulation due to broiler litter application in this Alabama survey was 30 g m^{-2} yr^{-1}, suggesting a retention rate in soil of ~8% of applied C in broiler litter.

SUMMARY AND CONCLUSIONS

Fertilization strategy had relatively minor impacts on soil bulk density, soil organic C concentration, and surface residue C and S contents. However, broiler litter application led to increased total S content in soil compared with inorganic and clover plus inorganic fertilization. Little evidence could be found of increased soil organic C concentration with broiler litter addition compared with inorganic fertilization. Harvest strategy had considerably larger impacts than fertilization strategy because of major differences in forage utilization and animal traffic. Soil bulk density was often lower under grazed than under ungrazed management at a depth of 0 to 2 cm, but the reverse effect occurred at a depth of 2 to 4 cm. Greater soil organic C concentration mitigated compaction with animal traffic at a depth of 0 to 2 cm. Soil organic C sequestration during the first 5 yr of management was similar between cattle grazing pressures (140 g m^{-2} yr^{-1}), but much reduced in unharvested (65 g m^{-2} yr^{-1}) and hayed (29 g m^{-2} yr^{-1}) management. Surface residue C accumulation at the end of 5 yr was inversely proportional to the level of forage utilization (i.e., 0.25 kg m^{-2} in unharvested, 0.21 kg m^{-2} in low grazing pressure, 0.15 kg m^{-2} in high grazing pressure, and 0.09 kg m^{-2} in hayed management). There was evidence to suggest that cattle grazing during the summer slightly increased soil compaction, but a period without animals in the winter relieved this compaction. However, cattle grazing had large positive impacts on soil organic C accumulation compared with unharvested and hayed management strategies. Further research is warranted to characterize the responses in soil and surface residue C and S contents to harvest management during a longer period of evaluation.

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